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Emissions of Metals and Organics from Four Municipal Wastewater Sludge Incinerators: Preliminary Data

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EMISSIONS OF METALS AND ORGANICS FROM FOUR MUNICIPAL WASTEWATER SLUDGE INCINERATORS - PRELIMINARY DATA

by

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KEY-WORD INDEX

Sludge, Incineration, Municipal Wastewater, Emissions, Metals, Organics, Multiple Hearth, Fluidized Bed.

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INTRODUCTION

The previous paper (1) at this conference described EPA's current approach to developing new sludge incinerator regulations. Concurrently with that regulatory effort, an emissions testing project was conducted which had the principal purpose of providing additional input to the incinerator regulations. Some of the data obtained was reported in the previous paper where it directly related to the proposed regulation.

The purpose of this paper is to discuss the emissions testing project in more detail. The project involved extensive testing for both metals and organics at four different incinerator sites. Three of the incinerators were multiple hearths and one was a fluid bed. Testing was done not only to satisfy the immediate needs of the regulations, but also to examine the effects of transients and look for causal relationships between operating conditions and emissions.

In order to evaluate the health risks from sludge incineration, data on air emissions are required. Previous data on air emissions from sewage sludge incinerators had three major deficiencies. First, emission tests were performed for short periods of time and during periods of best operation when emissions are likely to be at a minimum. Sewage sludge incinerators can experience a significant number of transients caused by changes in operating conditions. Data obtained during best operation may not be representative of actual long term emissions. Secondly, results from previous emissions tests are also highly variable, with little data documenting system operating conditions.

A third deficiency was that the data base contained very little data on emissions of organic compounds. In a multiple hearth incinerator, the flue gas from the combustion hearths passes through the upper hearths in order to dry sludge entering at the top. This design could potentially cause volatile organic compounds in the sludge to be carried out of the incinerator without being combusted. In

addition, there is some evidence that any organic compounds in the scrubber water may be stripped by the flue gas and emitted to the atmosphere.

The primary goal of this project was to gather emissions data to supplement the data base and eliminate some of its deficiencies. The specific objectives were the following:

1) Determine long-term emissions over a range of operating conditions;
2) Develop long-term and short-term emissions rates relating stack emissions to sludge composition;
3) Determine if short-term emissions data taken during periods of best operation can be used to accurately approximate long-term emissions;
4) Determine the efficiency of wet scrubbers in removing metal and organic emissions; and
5) Develop cause and effect relationships between incinerator operation and emissions.

TECHNICAL APPROACH

Selection of appropriate test sites was an important part of meeting the program objectives. A list of possible sites was compiled from previous Radian/EPA studies and from suggestions of individuals in these and other organizations. The potential test sites were then contacted by telephone for an initial screening. A number of site visits were then made to eventually select a total of four test sites. Site selection focused on multiple hearth incinerators because this is the most common type currently used. Ultimately, three multiple hearth incinerators and one fluidized bed unit were selected to allow a comparison in volatile compound emissions. The general characteristics of these four sites are shown in Table 1.

After site selection was completed, a test program was designed to meet the program objectives. Test matrices were developed for each site on the basis of the expected emission characteristics, the acceptability of scrubber inlet sampling

TABLE 1. INCINERATOR AND SLUDGE PARAMETERS

Design Parameter	Site 1	Site 2
Incinerator		
1. Manufacturer	Nichols	Hankin Environmental
2. Number of Hearths	6	8
3. Maximum design sludge feed rate, wet tons/hr.	7	9
4. Bottom ash production lb./hr.	1,053 (typical) 1,175 (maximum)	1,296 (typical) 1,800 (maximum)
5. Auxiliary fuel		
- Primary	Natural Gas	Natural Gas
- Backup		Diesel
Sludge Feed		
1. Sludge type	Conditioned & dewatered primary & secondary sludge	Conditioned & dewatered primary & secondary sludge
2. Solids, content, %	16 to 20	18 to 25
3. Volatiles content, % of dry solids	50 to 70	50 to 70
Control Device/Sampling		
1. Type	3 tray impingement wet scrubber	Venturi/3 tray impinge-wet scrubber
2. Scrubber pressure drop, in. W.C.	7-11	25 (For venturi, scrubber, and demister combined)
3. Sampling location	Stack	Control Device Inlet and Stack

TABLE 1. (continued)

Design Parameter	Site 3	Site 4
1. Manufacturer	Dorr-Oliver	Nichols
2. Number of Hearths	Fluid Bed, 22 ft. diameter	6
3. Maximum design sludge feed rate, wet tons/hr.	11	2.3
4. Bottom ash production lb./hr.	NA	360 (typical) 644 (maximum)
5. Auxiliary fuel		
- Primary - Backup	No. 2 Fuel Oil	Natural Gas
Sludge Feed		
1. Sludge type	Conditioned & dewatered primary & secondary sludge	Dewatered primary/ secondary blend
2. Solids, content, %	24 to 25	28
3. Volatiles content, % of dry solids	70 to 75	60
Control Device/Sampling		
1. Type	Venturi/3 tray impingement wet scrubber	Venturi/3 tray impingement wet scrubber Small afterburner (on standby)
2. Scrubber pressure drop, in. W.C.	15 (For venturi and scrubber)	25 (for venturi and scrubber)
3. Sampling location	Stack	Control device Inlet and Stack

locations, and the resources available for the project. Incinerator and general sludge characteristics for the test sites are presented in Table 1. Sludge feed rates and the results of sludge analyses for the actual tests are presented in Table 2.

At Site 1 and Site 3, testing was only performed at the scrubber exhaust. At Site 2 and Site 4, simultaneous tests at the inlet and outlet of the scrubber were performed to obtain data on scrubber efficiencies for both metals and organic compound emissions. At Site 4, the operation of an afterburner and a hot top hearth was also examined. At Sites 1 and 2, tests were performed during periods of steady-state operation, and also during more normal operation that included typical transients. At Site 1, the normal operation included a temporary feed cutoff, operation with high sludge moisture, and step changes in sludge feed rate. At Site 2, the normal operation included a feed cutoff with burnout, step changes in feed rate, and an increase in sludge moisture content.

SAMPLING AND ANALYTICAL PROCEDURES

Metals and organics samples were collected from the flue gas, sludge feed, scrubber influent and effluent water, and bottom ash. In order to relate emissions to incinerator and control device operation, key operating parameters were also monitored.

Quality assurance/quality control (QA/QC) was an integral part of sampling, analytical, and data reduction efforts. A QA/QC Project Plan was prepared and approved by EPA prior to the performance of on-site testing. The sampling and analytical methods are described briefly below.

Particulate and metals sampling was conducted at the scrubber inlet/outlet according to EPA Reference Method 12 (Alternate). This method is basically a modification of EPA Reference Method 5, with water in the impingers in the train replaced by 0.1 N nitric acid. A general discussion of methods for detecting

TABLE 2. SLUDGE FEED RATE AND ANALYSIS OF SLUDGE SAMPLES COLLECTED DURING TESTING

Parameter	Site 1	Site 2	Site 3	Site 4
Sludge Feed Rate (tons/hr.) (wet basis)	6.0	6.9	4.5	2.13
% Solids[a]	16.4	20.4	22.9	29.6
% Volatiles[a] (dry basis)	57.2	66.4	63.3	54.9
Heating value[b] J/gm. (wet basis)	3,062[b]	4,079[c]	5,307[b]	4,353[f]
Metals Concentration, u gm./gm.[d] (dry basis)				
Arsenic	ND	6.1	25.6	2.7
Beryllium	0.7	0.4	0.68	0.3
Cadmium	2.9	8.8	6.7	13
Chromium	213	82	284	69
Lead	98	99	347	302
Nickel	19.4	87	1222	272
Proximate Analysis[e]				
% Moisture	85.6	79.5	75.6	70.87
% Ash	5.2	7.4	10.6	10.05
% Volatile Matter	7.3	10.7	11.3	17.99
% Fixed Carbon	1.8	2.4	2.2	1.08

[a]Average of all samples collected during testing. These samples were analyzed at host site laboratory.

[b]Average of three samples collected on different days.

[c]Average of seven samples collected on different days.

[d]Average of sludge samples collected during metals testing.

[e]Based on analysis of a single sample.

[f]Average of eight samples collected on different days.

emissions are described in Reference (2). The particulate/metals samples were collected isokinetically in accordance with EPA Method 5 procedures. After gravimetric analysis of the filters, the particulate was digested in nitric acid and combined with the impinger solutions for analysis. Atomic Adsorption (AA) analysis was used for the determination of arsenic and lead. The determination of beryllium, cadmium, chromium, and nickel was done using the inductively coupled argon plasma (ICAP) technique.

Flue gas sampling for volatile organics was performed using the most recent method developed by U.S. EPA (3). This method, using the volatile organic sampling train or VOST, is designed to collect volatile organic compounds with boiling points between 30°C and 100°C. The organics are collected on two resin traps in series containing Tenax resin and charcoal. The sample is collected at 1 liter per minute for 20 minutes for each pair of traps. Four pairs of traps are collected per test run. The resin traps are analyzed by purge and trap followed by gas chromatography/mass spectrometry (GC/MS).

Semi-volatile samples of the flue gas were collected according to the semi-VOST method developed by U.S. EPA (4). The method is basically a modification of EPA Reference Method 5 with a condenser and adsorbent module added after the filter and before the impinger train to collect semi-volatile organics. The particulate filter, resin trap, and impinger solutions are extracted with organic solvent, concentrated, and analyzed by GC/MS.

Sampling for hexavalent chromium was performed at Sites 2 and 3 using an experimental modified EPA Method 5 train that had no particulate filter and 0.1 N sodium hydroxide in the impingers. Analysis of the samples for both hexavalent and trivalent chromium is then performed by a colorimetric technique. This sampling/analytical approach for hexavalent chromium was not successful, however, due to an interferant present in the final impinger solutions. This interferant

apparently formed some type of complex with either the hexavalent chromium or the colorimetric agent. For Site 4 testing, a particulate filter was reinserted in the train, but hexavalent chromium was not detected. More development of the method may be necessary for this particular application.

Grab samples of the process streams, which included feed sludge, bottom ash, and scrubber influent and effluent water, were collected at regular intervals during flue gas sampling. The sludge feed was sampled from the feed conveyor after dewatering. Bottom ash was collected from an intermediate point on the conveyor system prior to combination with other ashes. Scrubber water was collected from taps in the pipes. Hourly or 30 minute grab samples were combined at the end of a test run and analyzed following similar analytical schemes used for the flue gas samples.

Key operating parameters monitored included incinerator operating conditions, sludge feed characteristics, and wet scrubber system operating data. An example of the specific parameters monitored are included in Table 3. This list was modified on a site-specific basis.

TESTING SCHEDULE

At Site 1, four short-term metals tests were conducted under well controlled steady-state operation and an additional three tests were performed over extended periods of "normal" operation. The normal operation tests included transients due to temporary losses in feed, as well as wet sludge operation and step changes in sludge feed rates. Five volatile organics test runs, four at steady state and one under normal operation, were also performed at Site 1. Flue gas samples were only collected at the scrubber outlet.

At Site 2, metals tests conducted included four short-term test runs at steady-state operating conditions and three long-term tests under changing conditions. The process changes were deliberate and included step changes in sludge feed rates, a

TABLE 3. EXAMPLES OF PROCESS MONITORING DATA

Parameter	Parameter
Incinerator Operating Data	Wet Scrubber System Operating Data
Sludge Feed Totalizer (lb., wet basis)	Pressure Drop (in. H_2O)
Hearth Temperatures (°F)	Scrubber Influent Flow Rate (gpm)
Incinerator Outlet O_2 (by volume)	Scrubber Effluent Flow Rate (gpm)
Shaft Cooling Air Flow and Pressure	Scrubber Inlet Gas Temp (°F)
Natural Gas Flow Rate (cfm)	Scrubber Outlet Gas Temp (°F)
Incinerator Draft	
Sludge Feed Characteristics	
Moisture (wt %)	
Volatiles (wt %)	
Heating Value	

loss in feed that eventually led to burnout, and operation with wet sludge feed. Six volatile tests were also performed at Site 2. All tests performed at this site included simultaneous scrubber inlet and outlet sampling.

At Site 3, the site having a fluid bed incinerator, all operation monitored was essentially at steady-state, and consisted of measurements at the scrubber exhaust only. Three runs each were done for metals and volatiles.

At Site 4, operation was monitored for steady-state conditions only, but measurements were made both at the scrubber inlet and outlet, each with the afterburner fired and unfired. At the scrubber inlet and with the afterburner off, 6 runs were made for metals and 3 for volatiles. At the scrubber outlet with the afterburner off, 7 runs were made for metals and 3 for volatiles. At the scrubber inlet with the afterburner on, 3 runs were made for metals and 6 for volatiles. At the scrubber outlet with the afterburner off, 4 runs were made for metals and 3 for volatiles. The afterburner at this site was undersized so could not function as a typical afterburner. In order to simulate conditions more like normal afterburner operation, the top hearth temperature was raised. This provided data on what might be expected with a normal afterburner but also provided some indication of the merits of raising top hearth temperature as a general approach. The latter was accomplished through runs with the top hearth temperature raised, but with the afterburner off.

Semi-volatiles were measured at all sites, but as will be discussed later, few of the target compounds were detected. The amount of semi-volatiles measurement was then decreased as the test crew progressed to the later sites.

METALS EMISSIONS

Since the removal efficiencies over the entire incineration system for steady-state operation were discussed in the previous paper for both metals and organics,

we will concentrate here on other aspects of the data. It should be pointed out that for tests intended to compare different operating conditions every effort was made to hold all other conditions constant.

Metals emissions are reported in Table 4 in gm./hr. for all four sites. Comparisons between steady-state and normal (where transients are included) operation are possible with the data from Sites 1 and 2. Comparison of the results between steady-state and normal operation for these sites show slightly higher metals emission rates for arsenic, cadmium, and lead under normal operation. Emissions of beryllium, chromium, and nickel generally show similar values for both operating conditions. The slight increase in some of the metals may be related to level of operating temperature as discussed in the next section. It must also be emphasized that these comparisons between steady-state and normal operation where transients are included is based on a very gross analysis of long-term averages that may contain self-compensating effects. We doubt that this will be the final word on transients. More detailed resolution and analysis of the data is planned in order to try to determine the exact nature of the effects of various transients on incinerator emissions, and to estimate the impacts of prolonged operation away from optimum steady-state conditions.

At Site 4, the top hearth temperature was raised in conjunction with operating a relatively small afterburner in order to simulate the effect of a larger more normally sized afterburner. The raising of the top hearth temperature by itself should decrease organic emissions but could volatilize more metals from the sludge fed to the top hearth. The small afterburner would not be expected to affect metals. In addition to the top hearth temperature being raised along with operating the small afterburner ("Afterburner on" in Table 4), the furnace was also operated with the top hearth temperature raised but without the small afterburner on ("Hot furnace only" in Table 4). This latter operation was only examined at the scrubber

TABLE 4. METALS EMISSION RATES FOR DIFFERENT OPERATING CONDITIONS

	AVERAGE MASS EMISSION RATES (gm./hr.)						
	Site 1-Scrubber Outlet[a]		Site 2-Scrubber Inlet[a]		Site 2-Scrubber Outlet[a]		Site 3-Scrubber Outlet[c]
Metal	Steady State	Normal	Steady State[c]	Normal	Steady State	Normal	Steady State
Arsenic	0.06	0.10	1.9	2.0	0.45	0.53	0.0226
Beryllium	ND[b]	ND[b]	0.01	0.01	ND[b]	0.001	ND[b]
Cadmium	0.39	0.59	6.1	6.7	2.1	2.5	0.199
Chromium	0.39[c]	0.32	3.6	3.5	0.58[d]	0.38[d]	0.65
Lead	16.6	30.9	16.8	26.2	5.2	5.9	0.346
Nickel	0.26[c]	0.20	4.1	4.4	1.4[d]	1.0[d]	5.76

TABLE 4. (continued)

Metal	Site 4 Scrubber Inlet Steady-State Afterburner Off[e]	Site 4 Scrubber Outlet Steady-State Afterburner Off	Site 4 Scrubber Inlet Steady-State Afterburner On[f]	Site 4 Scrubber Outlet Steady-State Afterburner On[f]	Site 4 Scrubber Outlet Steady-State Hot Furnace Only[g]
	AVERAGE MASS EMISSION RATES (gm./hr.)				
Arsenic	0.161	0.025	0.056	0.027	0.024
Beryllium	ND[b]	ND[b]	ND[b]	ND[b]	ND[b]
Cadmium	3.142	1.566	2.928	1.408	1.481
Chromium	3.152	2.813	1.684	2.973	2.278
Lead	37.212	17.935	56.891	22.500	30.316
Nickel	3.498	0.252	1.845	0.206	0.356
Copper		3.130		3.679	4.864
Sellenium		ND[b]		ND[b]	ND[b]
Zinc		27.134		12.655	30.435

[a]Averages based on 4 test runs for steady state operation and 3 test runs for normal operation unless otherwise noted.
[b]Not detected.
[c]Based on 3 valid samples.
[d]Based on 2 valid samples.
[e]Top hearth at normal conditions of 1100-1400°F.
[f]Afterburner on and top hearth temperature at 1400-1700°F.
[g]Afterburner off but top hearth temperature at 1400-1700°F.

outlet, however, and metals emissions there did not seem to be affected by either mode of operation.

At the scrubber inlet, where the effect of the hotter top hearth should be more pronounced, samples were collected under afterburner on and afterburner off conditions, the latter having the top hearth elevated in temperature. Comparing these two kinds of runs, the only increase in metals emissions seen in Table 4 was for lead.

EFFECT OF TEMPERATURE ON METALS EMISSIONS

A comparison of the concentration of metals in flue gas particulates (μ gm. of metal/gm. of particulate) shows a much more dramatic effect of operating conditions on the characteristics of metals emissions. This comparison was made for data from Site 1 and Site 2 where steady-state and normal operation were examined and included the widest variation in operating conditions. Data comparing metal-to-particulate ratios for Site 1 and Site 2 steady and normal operation are presented in Table 5. These data show a consistent and statistically significant trend of metals enrichment for arsenic, cadmium, and lead under conditions that included transients at all three test locations.

Comparisons of flue gas metals-to-particulate ratios in Table 5 for the scrubber inlet and scrubber outlet at Site 2 show that particulates leaving the scrubber have a significantly higher concentration of metals. Venturi and tray scrubbers are generally less effective at removing finer particulates. Thus, the observed increase in metals concentration for particulate exiting the scrubber indicates that the metals are primarily associated with the finer particulates. This is consistent with other combustion processes and is likely due to the greater surface area per unit volume (or mass) presented for absorption or condensation by smaller particulates.

This enrichment of metals on fine particulate may be related to incinerator

TABLE 5. COMPARISON OF PARTICULATE METALS CONCENTRATIONS FOR DIFFERENT OPERATING CONDITIONS[a]

METALS-TO-PARTICULATE RATIO (μ gm. METAL/gm. PARTICULATE)

	Site 1 - Scrubber Outlet		Site 2 - Scrubber Outlet		Site 2 - Scrubber Inlet	
Metal	Steady State	Normal	Steady State	Normal	Steady State[c]	Normal
Arsenic	12.2	26.9	877	1,010	174	223
Beryllium	0.6	0.2	NA[b]	2.1	1.0	1.2
Cadmium	87.2	157	4,150	5,100	557	735
Chromium	42.8[c]	85.3	1,190[d]	803[d]	325	361
Lead	3,720	7,980	8,250	11,560	1,530	2,390
Nickel	62.6[c]	47.0	2,770[d]	1,950[d]	375	539
Temperature:[e]						
Hearth 3	NA[f]	NA[f]	1,382	1,549	1,383	1,550
Hearth 4	1,516	1,499	1,633	1,575	1,610	1,581
Average	--	--	1,507	1,562	1,496	1,566

[a]Averages based on four test runs for steady state operation and three test runs for normal operation unless otherwise noted.
[b]Not applicable. Metal was not detected in flue gas sample.
[c]Based on three valid samples.
[d]Based on two valid samples.
[e]Combustion took place primarily on Hearth 4 for both furnaces.
[f]Not available. The thermocouple for this hearth was found to be inaccurate.

temperatures. As shown in Table 5, the temperature on the hearth above the combustion hearth averaged higher during the normal tests at Site 2. The effect of temperature on metals enrichment was investigated for the Site 2 data set by plotting metal-to-particulate ratios against temperature for individual test runs under all operating conditions. The temperature used in this analysis was the average of the combustion hearth temperature (hearth #4) and the temperature on the next hearth up (hearth #3).

The results of this investigation suggest that for at least lead, the observed enrichment is related to temperature. Data showing the effect of temperature on lead enrichment in combustion gas particulates are shown in Figure 1 for the Site 2 scrubber inlet and outlet locations, respectively. Average temperatures for the two hearths for individual runs are used in Figure 1. The trend of lead enrichment with higher temperatures was found to be statistically significant at the 95 percent confidence level. A similar investigation for the Site 1 data gave inconclusive results because data from the thermocouple on the hearth directly above the combustion hearth was inaccurate.

Data for cadmium are also shown in Figure 1. Although the least square regression for the cadmium data gives a positive slope, the slope was not found to be statistically greater than zero at the 95 percent confidence level. No temperature effect would be expected for beryllium, chromium or nickel since these metals did not show evidence of enrichment. No temperature effect was found for arsenic either.

SCRUBBER REMOVAL EFFICIENCIES

Scrubber removal efficiencies for metals and particulates could be calculated for Sites 2 and 4 because inlet and outlet measurements were made at those sites. Those data for Site 2 and Site 4 are presented in Table 6. The Site 2 data include both steady-state and normal operating conditions. Total particulate removals for

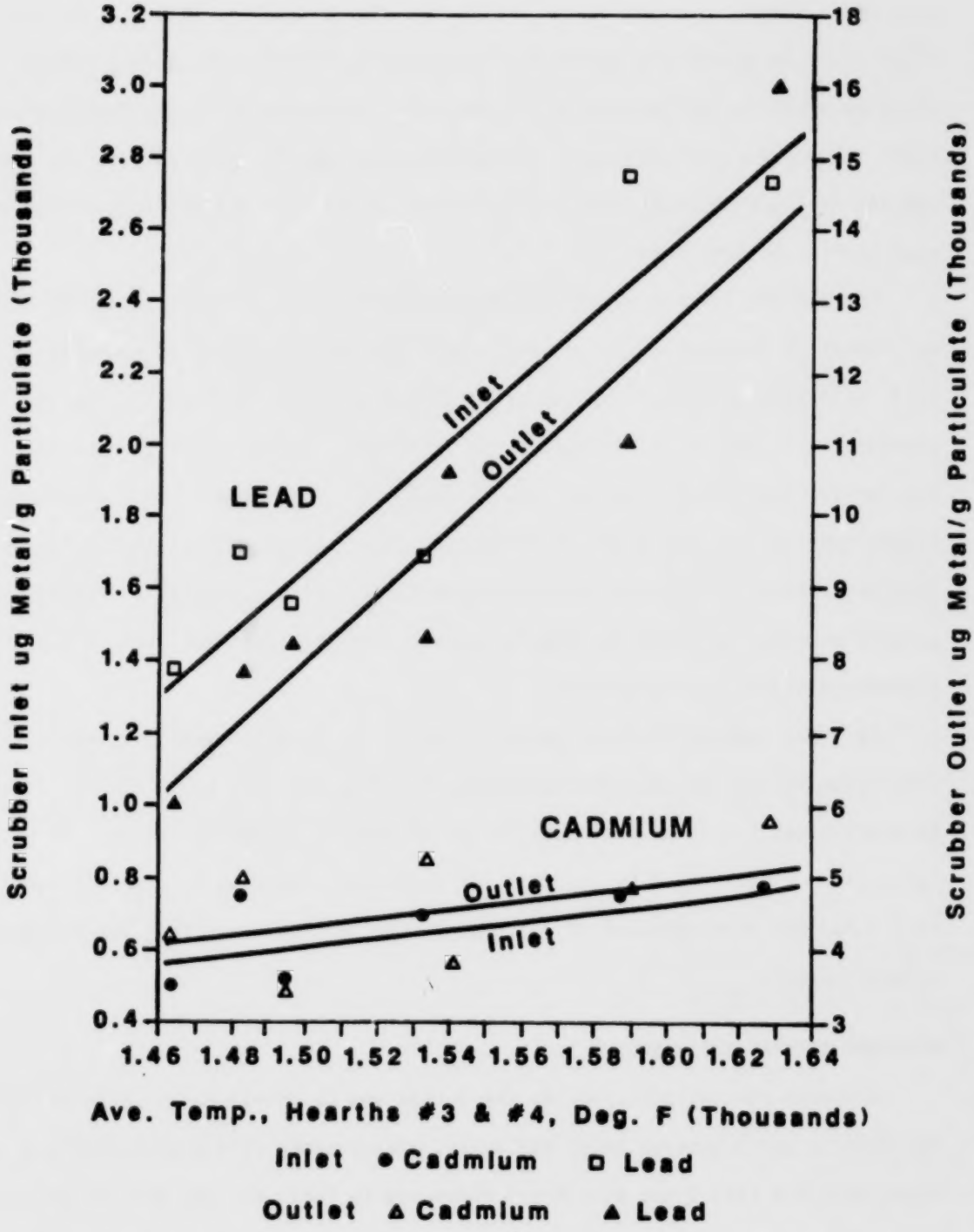

FIGURE 1. METAL-TO-PARTICULATE RATIOS VERSUS AVERAGE HEARTH TEMPERATURE AT SITE 2.

TABLE 6. METALS/PARTICULATE REMOVAL EFFICIENCIES FOR SCRUBBING SYSTEMS

Metal	Scrubber Removal Efficiency (%)[a] Site 2 Steady State	Site 2 Normal	Site 4 Steady State
Arsenic	77.2	77.7	84.5
Beryllium	ND[b]	87.9	ND[b]
Cadmium	62.8	68.1	50.2
Chromium	79.1[c]	90.6[c]	30.7
Lead	76.5	78.1	51.8
Nickel	53.1[c]	80.3[c]	92.8
Total Particulates	95.2	95.4	96.8

[a]Averages based on 4 test runs for steady state operation and 3 test runs for normal operation unless otherwise noted.

[b]ND = not applicable. Compound not detected at outlet.

[c]Based on two valid samples.

the two test conditions at Site 2 are essentially identical at 95 percent. The average particulate removal at Site 4 is a little higher. Removal efficiencies for the metals are similar under both operating conditions at Site 2, with slightly higher removals seen for chromium and nickel during the normal tests. Efficiencies for these two metals are based on only two valid analyses, however, and no statistical comparisons can be made. At Site 4, the removal efficiencies for cadmium, chromium, and lead are lower, while that for nickel is higher.

VOLATILE AND SEMI-VOLATILE ORGANIC EMISSIONS

Volatile organic compound emissions data for the scrubber outlet at all four test sites are presented in Table 7. The target organic compounds shown in the table were determined based on specific compounds of interest to the U.S. EPA Office of Water Regulations and Standards, compounds of interest to the U.S. EPA Office of Air Quality Planning and Standards, and compounds identified as potential pollutants by combustion testing of the sludge performed at the University of Dayton. Three of the compounds, acetonitrile, 2-butanone and pyridine, were additional ones for Site 4 only, being added as the result of the testing at the University of Dayton. Most of the target volatile compounds for this program were found in the scrubber outlet flue gas at all test sites. Comparison of emission rates for the sites shows slightly higher emissions from Site 1. At all multiple hearth test sites, acrylonitrile, benzene, and toluene emissions exceeded 4 gm./hr. Vinyl chloride emissions were greater than 4 gm./hr. at Sites 1 and 2 and 2-butanone emissions were above this value at Site 4. This emission rate is comparable to the mass emission rate observed for lead and cadmium. Volatile organic emissions were generally much lower at Site 3, the fluid bed site, as was expected. Volatile organic compounds detected in the sludge feed included: tetrachloroethene and trichloroethene at Site 1, chlorobenzene, ethylbenzene, methylene chloride, toluene, and trichloroethane at Site 2; toluene, tetrachloroethene, ethylbenzene, methylene chloride, chloroform,

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TABLE 7. VOLATILE EMISSIONS AT THE OUTLET - NORMAL SCRUBBING

	Mass Emission Rate (gm./hr.)			
VOLATILE COMPOUND	Site 1	Site 2	Site 3	Site 4
Acetonitrile	NA[a]	NA[a]	NA[a]	6.497
Acrylonitrile	13.3	12.6	ND[b]	21.582
Benzene	16.7	5.3	0.401	4.398
2-Butanone (MEK)	NA[a]	NA[a]	NA[a]	5.525
Carbon Tetrachloride	0.10	0.003	0.013	0.0092
Chlorobenzene	1	0.36	0.0057	0.536
Chloroform	4.8	0.61	3.922	0.251
1,2-Dichloroethane	0.026	ND[b]	ND[b]	ND[b]
Trans-1, 2-Dichloroethene	0.20	0.009	ND[b]	0.0297
Ethylbenzene	1.7	0.45	0.0189	1.063
Methylene Chloride	2.2	0.58	0.0705	1.470
Pyridine	NA[a]	NA[a]	NA[a]	ND[b]
Tetrachloroethene	12.2	0.88	0.1515	0.892
Toluene	5	11.9	0.0673	4.145
1,1,1-Trichloroethane	0.29	0.02	0.0429	1.104
Trichloroethene	1.4	0.16	0.0088	1.512
Vinyl Chloride	5.3	8.0	0.0227	1.014

[a]Not analyzed for.
[b]Not detected. Compound not detected in flue gas.

and benzene at Site 3; and toluene, tetrachloroethane, trichloroethene, and methylene chloride at Site 4.

From the data collected at Site 4, it is possible to calculate removal efficiencies for two other approaches to control of volatile organics. These two options were operation with a hot top hearth and operation with that combined with the small afterburner to simulate the effect of a larger more normal sized afterburner. The calculated efficiencies for these two options are shown in Table 8. Although these values were calculated from non-simultaneous measurements, it appears that the top hearth operation alone would very likely result in high removals of a majority of the volatile organics. The combination operation intended to simulate a normal afterburner indicates high calculated removals for most of the volatile organics.

As an example of a material balance, volatile organic compound mass flow rate data for Site 2 are presented in Table 9. Measured values for concentrations of target compounds are listed as mass rates wherever the compound was detected. For non-detected volatiles, the mass rate corresponding to the detection limit is listed for comparison with the flue gas emission rates.

The data presented in Table 9 can be used to assess whether the volatile compounds emitted at the scrubber outlet may have come directly from the sludge or if these compounds could be products of incomplete combustion. A review of the mass balance data suggests that acrylonitrile, benzene, and vinyl chloride may all be products of incomplete combustion. The mass rates of these compounds entering with the sludge (at either the actual values or the detectable limits) are much less than the mass rates found at the scrubber inlet. Emission rates for chlorobenzene, ethylbenzene, methylene chloride, tetrachloroethene and toluene are all well below the mass rates of these compounds in the sludge feed.

Review of the Site 2 data in Table 9 for the scrubber water and flue gas

TABLE 8. VOLATILE ORGANIC REMOVAL EFFICIENCIES FOR HOT FURNACE AND AFTERBURNER COMBINATIONS AT SITE 4.

Volatile Compound	Cool Furnace Base gm./hr.	Hot Furnace only gm./hr.	Removal Efficiency (%)	Hot Furnace-Afterburner gm./hr.	Removal Efficiency (%)
Acetonitrile	58.823	3.615	93.85	0.881	98.5
Acrylonitrile	30.783	11.534	62.5	1.625	94.7
Benzene	5.802	0.817	85.9	0.449	92.3
2-Butanone (MEK)	9.048	ND[a]	100	0.544	94.0
Carbon Tetrachloride	0.176	0.225	-27.8	0.0471	73.2
Chlorobenzene	1.118	0.0577	94.8	0.0217	98.1
Chloroform	0.0803	0.0336	-	0.0138	58.2
1,2-Dichloroethane	ND[a]	ND[a]	-	ND[a]	-
Trans-1,2-Dichloroethane	ND[a]	ND[a]	-	ND[a]	-
Ethylbenzene	1.975	ND[a]	100	0.0631	96.8
Methylene Chloride	0.0919	0.0138	85.0	0.0131	85.7
Pyridene	ND[a]	ND[a]	-	ND[a]	-
Tetrachloroethene	0.985	0.050	94.9	0.00178	99.8
Toluene	3.309	0.0627	98.1	0.330	90.0
1,1,1-Trichloroethane	0.0507	0.0365	28.0	0.00506	90.0
Trichloroethene	0.298	0.0415	86.1	0.00247	99.2
Vinyl Chloride	2.667	ND[a]	100	ND[a]	100

[a]Not detected - assumed zero

TABLE 9. COMPARISON OF AVERAGE VOLATILE ORGANIC COMPOUND MASS FLOW RATES - SITE 2

Volatile Compound	Sludge[a] Feed MDL (mg./hr.)	Actual[b] Sludge Feed (mg./hr.)	Flue Gas Inlet (mg./hr.)	Flue Gas Outlet (mg./hr.)	Scrubber[b] Water Influent (mg./hr.)	Scrubber[b] Water Effluent (mg./hr.)	Scrubber[a] Water MDL (mg./hr.)
Acrylonitrile	[12,599]	ND[c]	31,830	12,740	2,240	14,700	[680]
Benzene	[374]	ND	12,450	5,290	ND	ND	[1,500]
Carbon Tetrachloride	[562]	ND	3.8	2.6	ND	ND	[953]
Chlorobenzene	[750]	3,330	365	3.56	ND	ND	[2,040]
Chloroform	[437]	ND	6.3	609	871	ND	[544]
1,2-Dichloroethane	[1,180]	ND	ND	ND	ND	ND	[953]
Trans-1,2-Dichloroethene	[1,440]	ND	7.9	9.0	ND	ND	[102]
Ethylbenzene	[1,620]	10,160	323	445	ND	ND	[2,450]
Methylene Chloride	[1,180]	18,900	1,182	577	1,630	3,080	[953]
Tetrachloroethene	[1,370]	3,590	484	882	ND	ND	[1,390]
Toluene	[1,370]	524,000	19,590	11,920	ND	ND	[2,040]
1,1,1-Trichloroethane	[562]	5,650	4.5	20.1	ND	ND	[1,290]
Trichloroethene	[1,440]	ND	68.6	157	ND	ND	[646]
Vinyl Chloride	[3,760]	ND	11,620	7,974	ND	ND	[170]

[a] Mass rate calculated as if compound was present at the minimum detection level. Presented for comparison only.
[b] Mass rate calculated based on amounts actually detected in the samples.
[c] Not detected.

outlet streams indicates that 1) acrylonitrile and methylene chloride are scrubbed from the flue gas by the scrubber and 2) chloroform present in the influent water is stripped from the water and emitted in the flue gas.

Only a few of the target semi-volatile compounds were detected as emissions at each site. At Site 1, bis (2-ethylhexyl) phthalate, 1,2-dichlorobenzene, 1,3 dichlorobenzene, and 1,4 dichlorobenzene were detected in various samples but none of the compounds were above detection limits in all of the samples collected from the incinerator stack. Site 2 showed only a few of the target compounds present in the stack emissions. These were naphthalene, phenol, 2-nitrophenol, bis (2-ethylhexyl) phthalate, and isomers of dichlorobenzene. Bis (2-ethylhexyl) phthalate was also found at both Sites 1 and 2 in the flue gas, sludge feed, and water samples. However, this particular compound is a contaminant found in plasticizers. The levels found may also have been partially due to sample contamination by plastic containers, etc., used in sampling and analysis. At Site 3, the only semi-volatile detected in the emissions was the bis (2-ethylhexyl) phthalate. At Site 4, phenol and naphthalene were the only semi-volatiles present in quantities above detection limits. Dioxin/furan testing was done at only one site, Site 4. Amounts found seemed to be in the range of other incinerators tested prior to the present project.

CONCLUSION

A summary of the conclusions from the preliminary data analysis is as follows:

- Slight increases in average metals emissions is observed for operation that included transients. On the other hand, this increase was not found to be highly significant based on statistical tests. This conclusion is based on overall averages, however, and finer resolution of the unsteady-state data may alter this preliminary indication.

- The concentration of lead in particulates was found to increase with temperature.
- Emissions of volatile compounds from four incinerators could be characterized.
- Additional data on scrubber efficiencies were obtained.
- Efficiencies were also obtained for a simulated afterburner and for the effect of raising the top hearth temperature.
- Some of the volatile compounds appear to be products of incomplete combustion.

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